Charged Particle Sources and Beam Technology

Light Sources III
Future Accelerators / Current Topics of R+D

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Topics

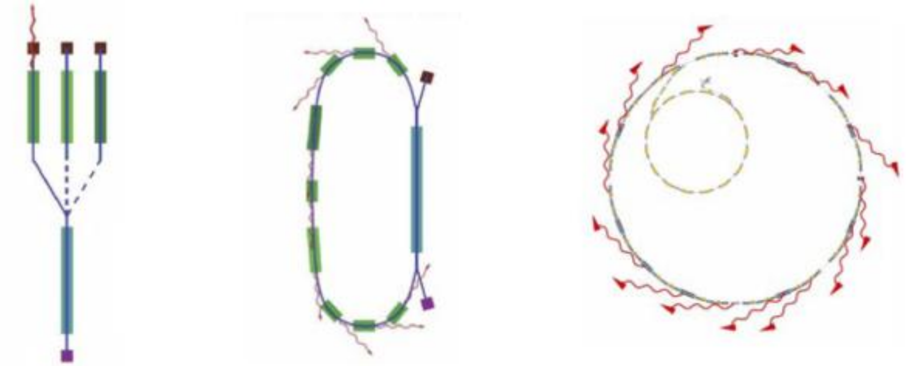
- Light Sources – continued from last week
  - —4th generation SR sources
    - Ultimate Storage Rings
    - ERLs
    - FELs (seeded)
    - Laser Plasma Wakefield Accelerators (driving FELs)
  - —R+D issues
    - Sources
    - Beam Dynamics

- Summary

Lectures are posted at
http://als.lbl.gov/als_physics/robin/Teaching/NUC%20282c.html

Outline - a variety of synchrotron radiation source concepts to pursue

- **(Ultimate) Storage rings**
- **Energy recovery linac (ERL)**
- **Free electron laser (FEL)**
- Laser wakefield accelerator
- Optical manipulation of electron beams



Figures of merit

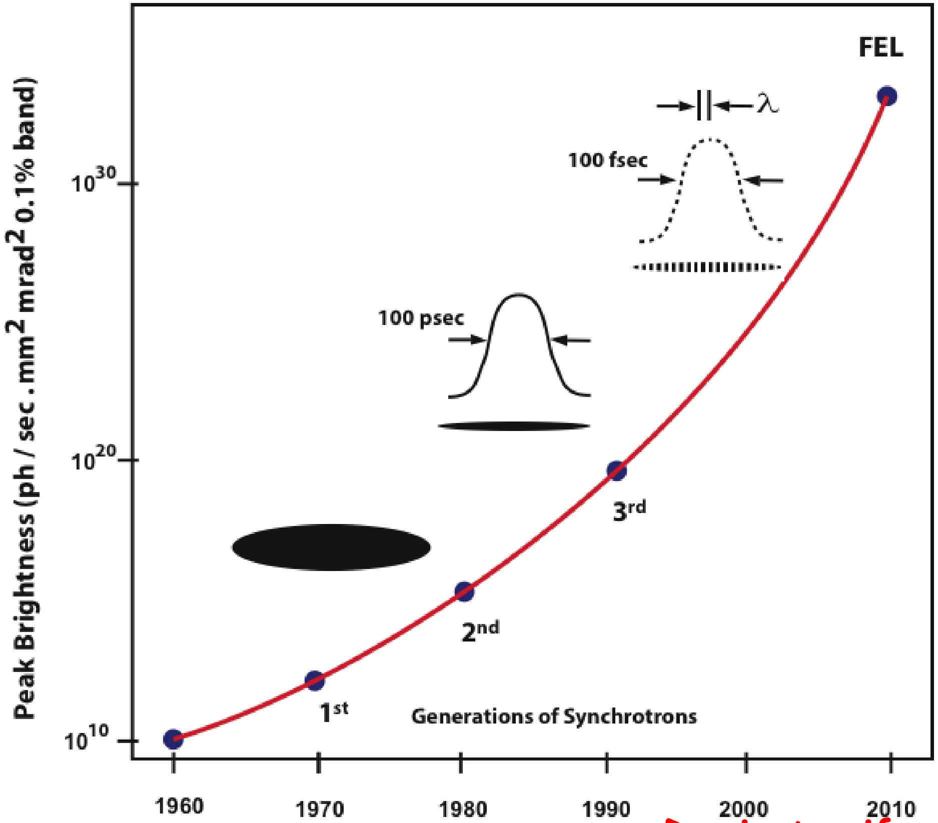
- Average and peak flux
- Average and peak brightness
- Pulse repetition rate
- Temporal coherence
- Bandwidth
- Spatial coherence
- Pulse duration
- Synchronization
- Tunability
- # beamlines
- Beam stability

Future generations of light sources will likely utilize novel techniques for producing photons tailored to application needs

Different operating modes

Different facilities

Evolution of light sources - seeded FEL provides some capabilities not available from other sources



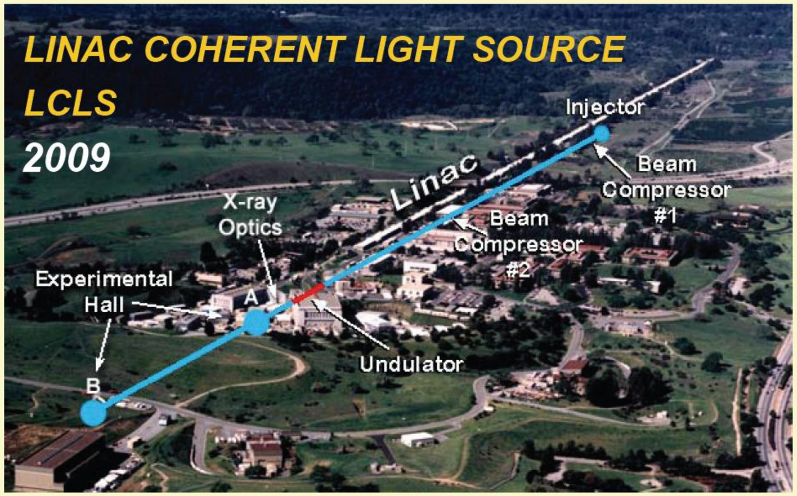
Dominates if $\sigma_z < \lambda$

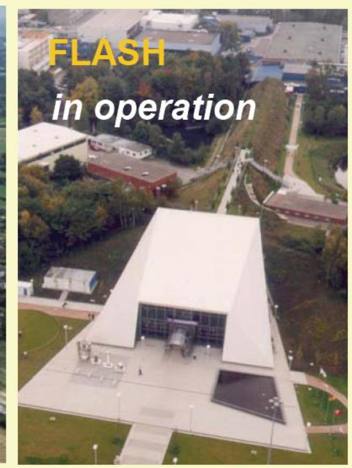
$$I_{total}(\omega) = \{N + N(N-1)|g(k)|^2\} I_e(\omega)$$

$$g(k) = \int_{-\infty}^{\infty} \rho(z) e^{ikz} dz$$

- **Free Electron Laser (FEL)**
  - Enhance coherence at shorter wavelengths by modulation of the charge within a bunch
- ***Seeded* FEL provides additional capabilities essential to explore the proposed science:**
  - Control of pulse duration
  - Temporal coherence and narrow linewidth
  - Harmonic generation of shorter wavelengths
  - Precise synchronization
  - Shorter gain length

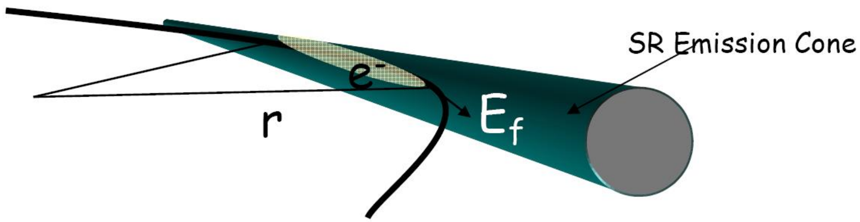
‘1st generation’ SASE FEL Facilities

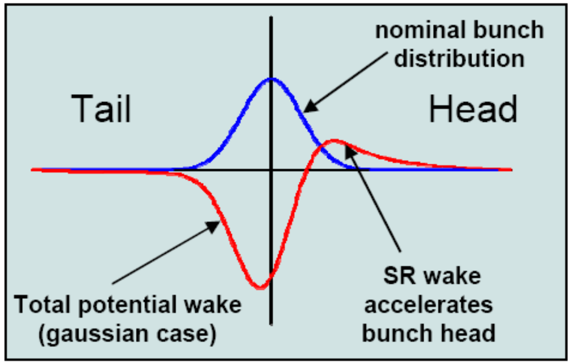




Reminder: SR Wake Field

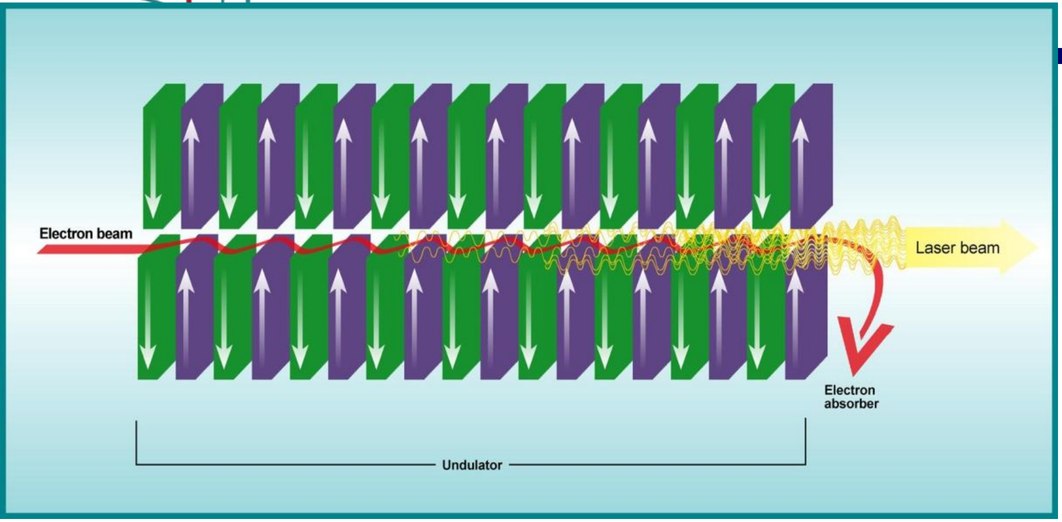
- The wake field due to synchrotron radiation, belongs to the category of the wakes that propagates with the beam. Such a wake is important only for the relativistic particle case.
- Relativistic particles on a curved trajectory emit synchrotron radiation (SR). The SR fields propagates in a cone of emission centered on the tangent to the beam trajectory at the emission point and with ~ $1/\gamma$ aperture.

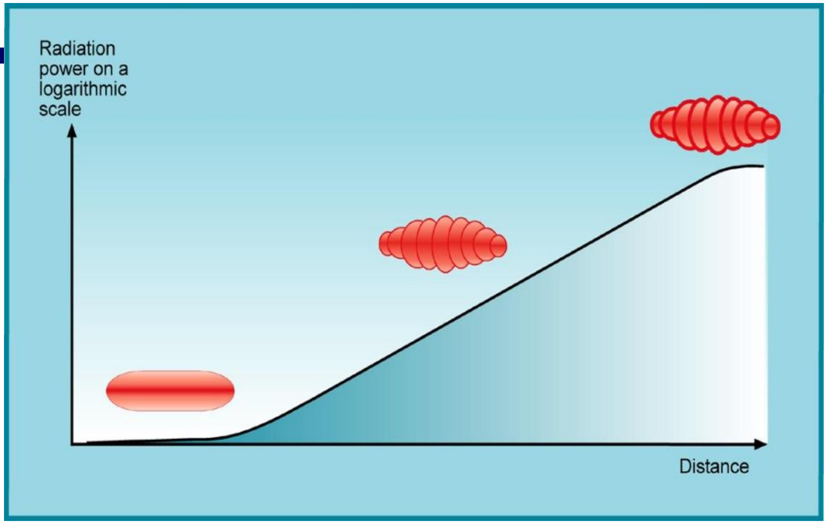


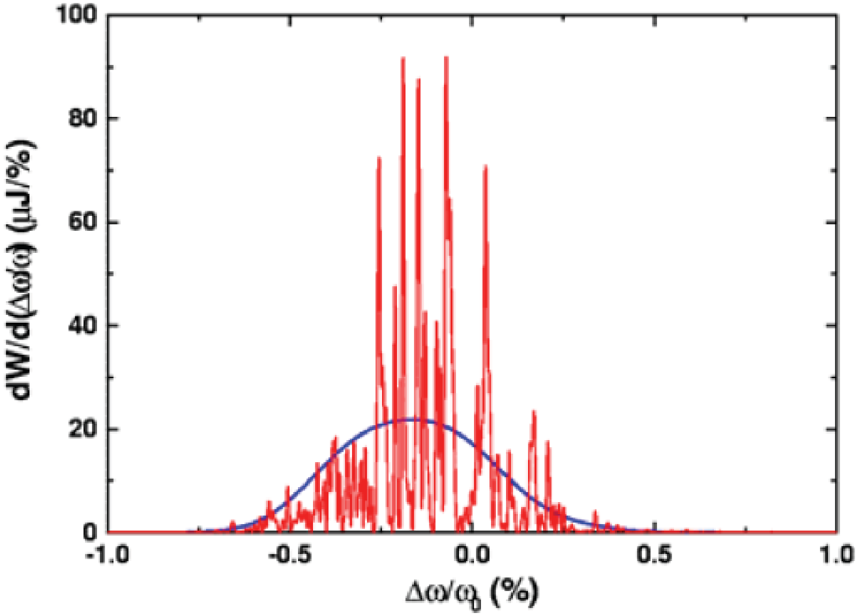


- The fields propagate at the speed of light, while the particles move on the curved trajectory. For this reason, even if the particles are relativistic the projection of their speed on the tangent direction is smaller than *c*.
- In other words, the SR wake field due to a particle in the tail of the bunch can reach and interact with a particle in the head! This is exact the opposite of what happens with vacuum chamber wakes.

SASE FEL

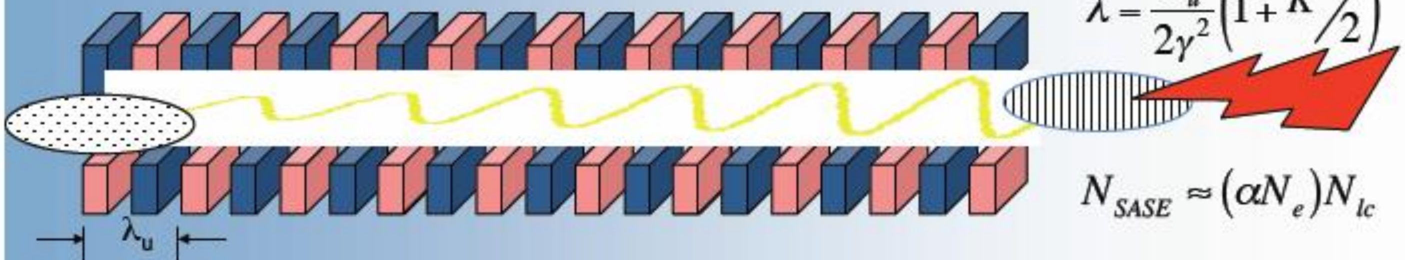






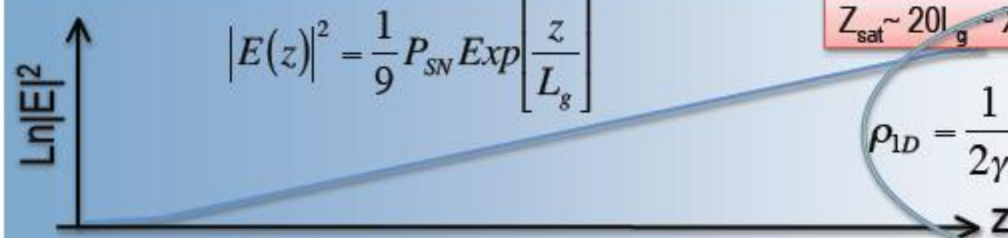
- Beam entering undulator emits spontaneous synchrotron radiation
- Radiation interacts with bunch, creating microstructure
- Particle within microstructure start to emit coherently – exponential gain until saturation
- Critical: Bunch length, energy spread, emittance (transverse size*divergence)

SASE: Self Amplified Spontaneous Emission



$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + K^2/2\right)$$

$$N_{SASE} \approx (\alpha N_e) N_{lc}$$



$$|E(z)|^2 = \frac{1}{9} P_{SN} Exp\left[\frac{z}{L_g}\right]$$

$Z_{sat} \sim 20 L_g \sim \lambda_u/\rho_{1D}$

$$\rho_{1D} = \frac{1}{2\gamma}\left[\frac{I_{peak}}{I_A}\frac{\lambda_u^2 K^2 [JJ(K)]^2}{8\pi^2 \varepsilon_x \beta_x}\right]^{1/3}$$

Power Gain Length: $L_g \approx \frac{\lambda_u}{4\pi\sqrt{3}\rho_{1D}}$

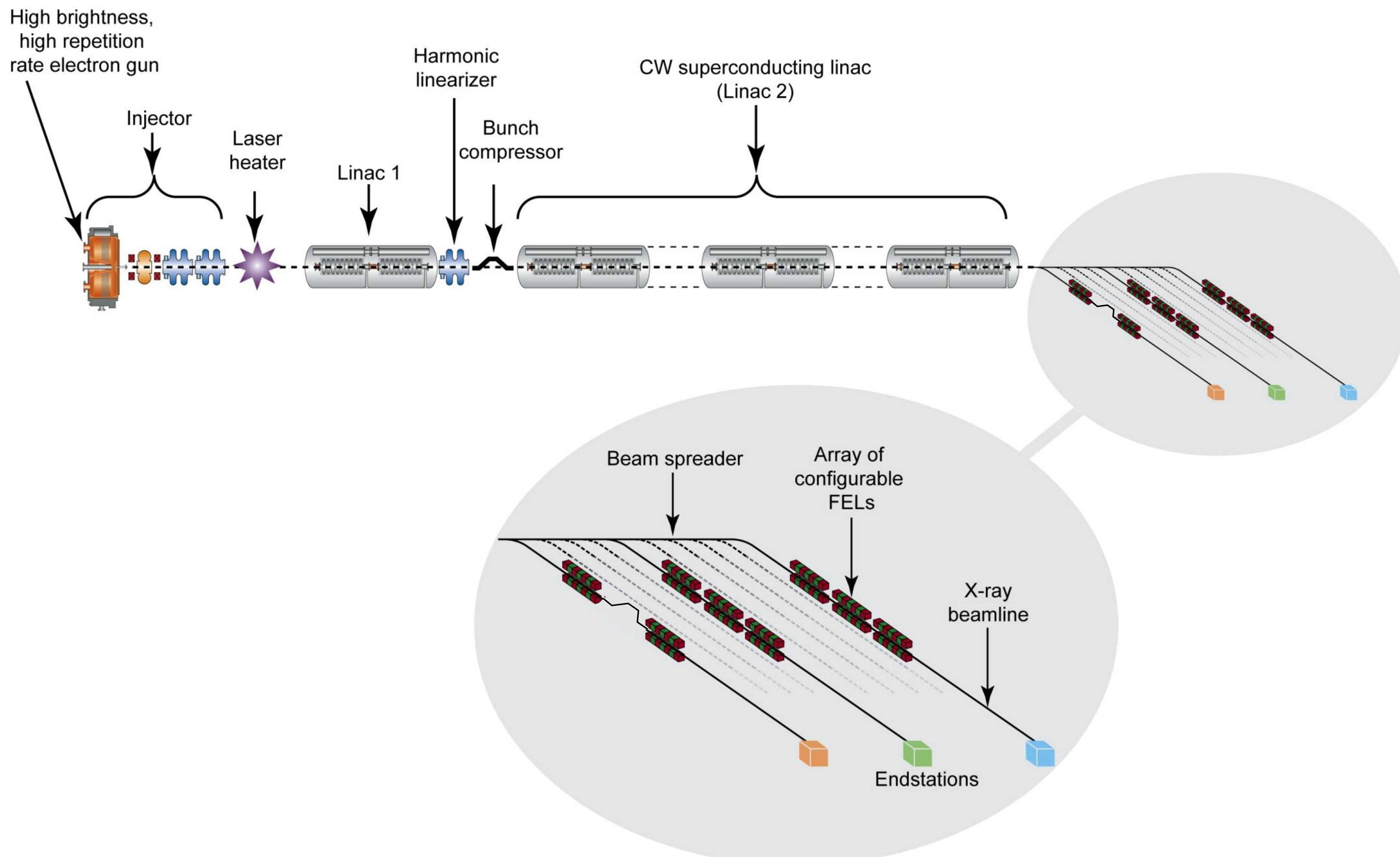
FEL Bandwidth: $\frac{\sigma_\omega(z_{sat})}{\omega} \approx \rho_{1D}$

Cooperation Length: $L_c \approx \frac{\lambda}{\lambda_u} L_g = \frac{\lambda}{4\pi\sqrt{3}\rho_{1D}}$

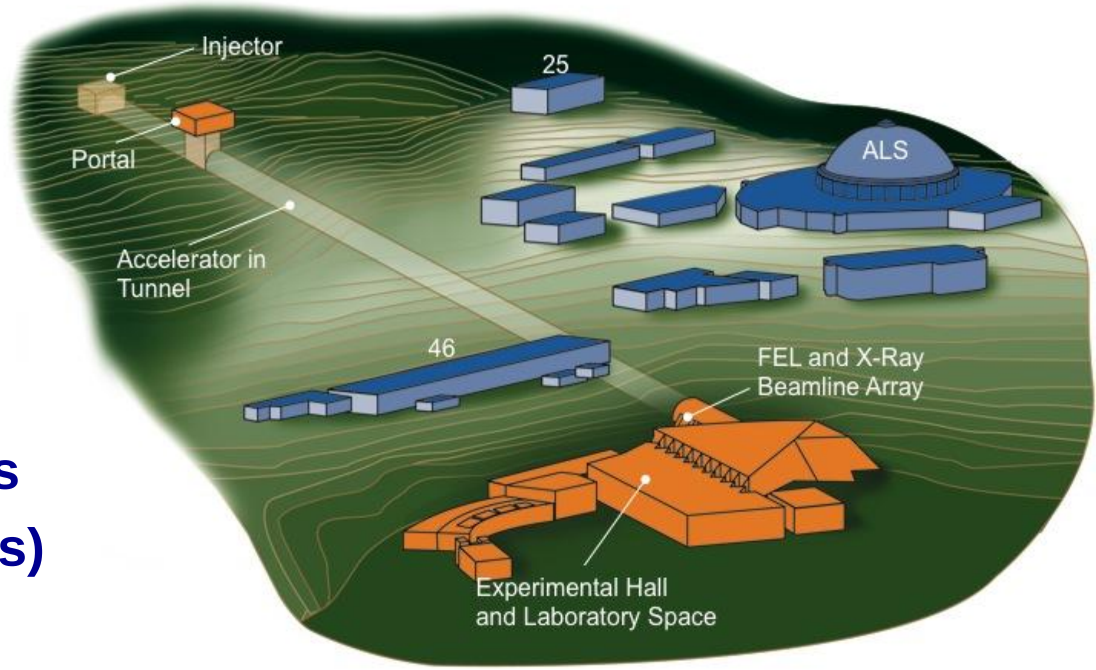
FEL Efficiency: $P_{peak}(z_{sat}) \approx \rho_{1D} E_e I_{peak}$

Bonifacio, Pellegrini & Narducci 1984

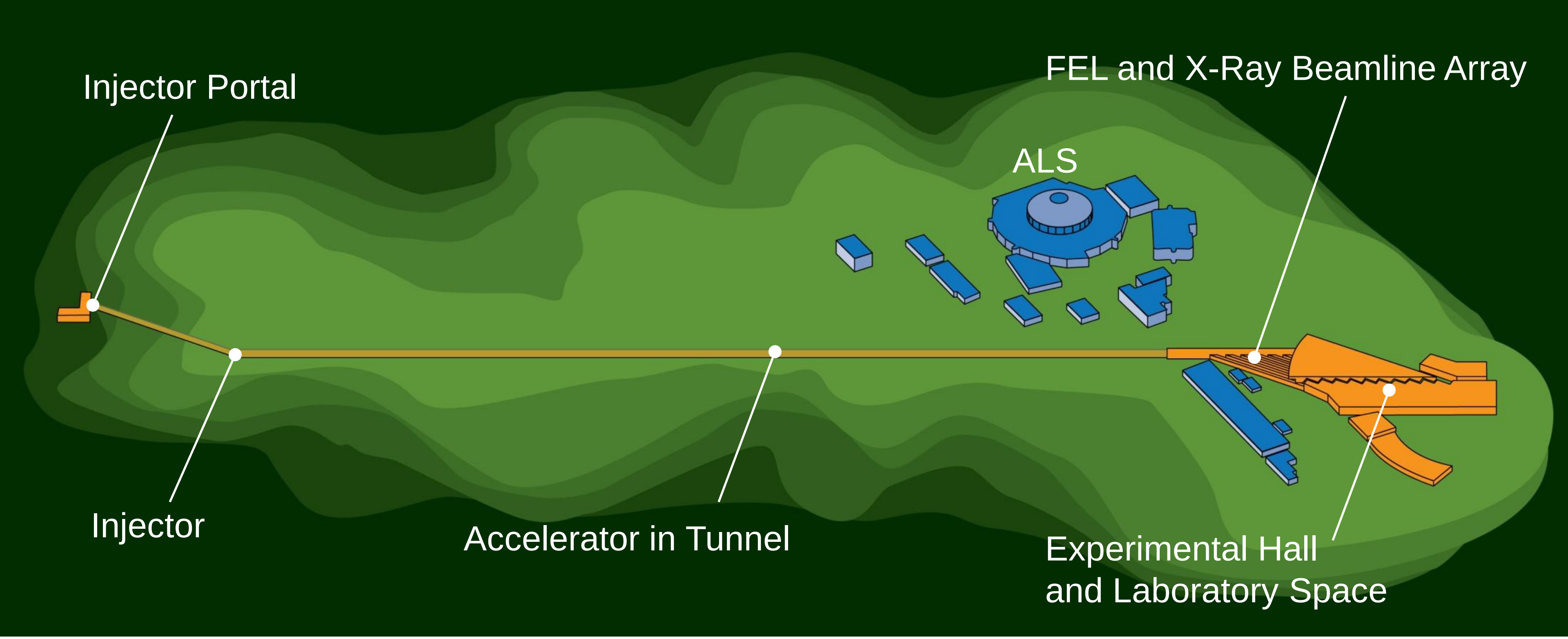
Schematic of a high rep-rate, multi-user FEL array

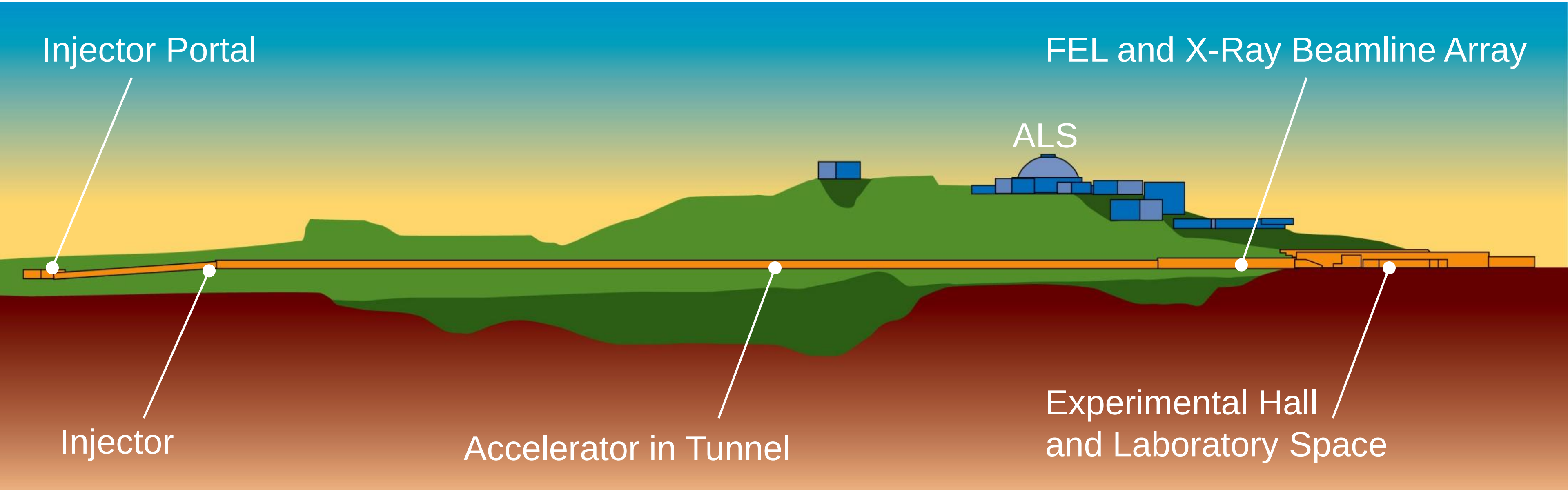


LBNL's Next Generation Light Source



- Coherent soft x-ray laser
- 10 eV - 1 keV range
  - harmonics to 5 keV
- Seeded by optical lasers
- Multiple, simultaneous beams
  - with different properties
- Time-bandwidth limited pulses
  - Ultrashort (~100 attoseconds)
  - Narrow bandwidth (meV)
- High peak power - for nonlinear optics (~ 1 GW)
- Control of peak power - 10–1000 MW to minimize sample damage
- High average power - for low scattering rate experiments (~ 1–10 W)
- High repetition rate - for good S/N (~100 kHz–MHz+ for some beamlines)
- Capable of serving large number of users (~ 2000 users/year)


Injector Portal
FEL and X-Ray Beamline Array
ALS
Injector
Accelerator in Tunnel
Experimental Hall
and Laboratory Space


Injector Portal
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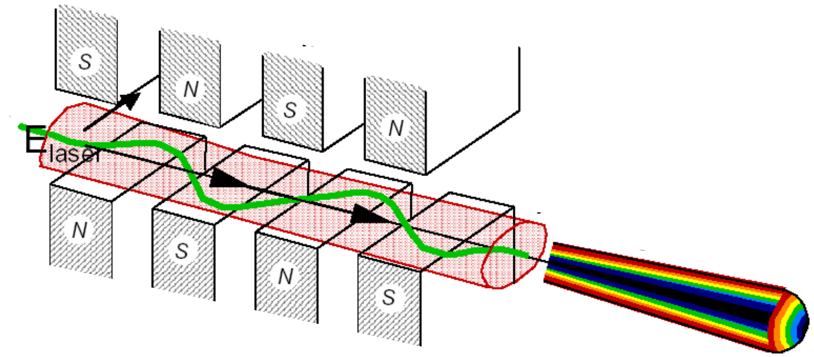
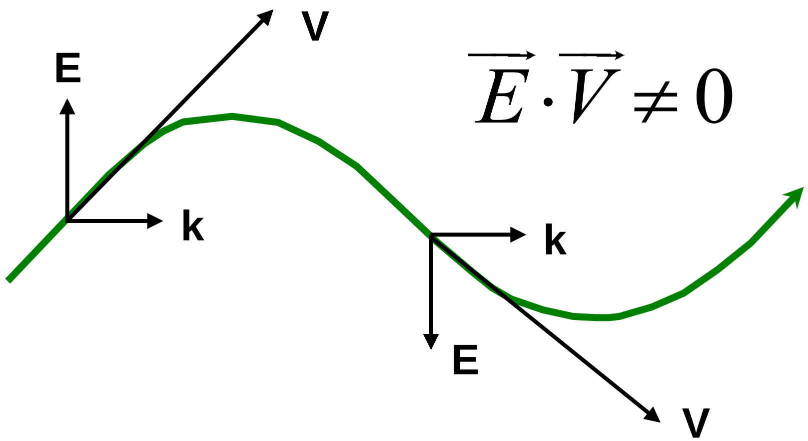
Optical manipulations

LASER PULSE USED TO MANIPULATE ELECTRON BEAM ENERGY





$$\vec{E}\cdot\vec{V}\neq 0$$

Wiggler period

Undulator parameter

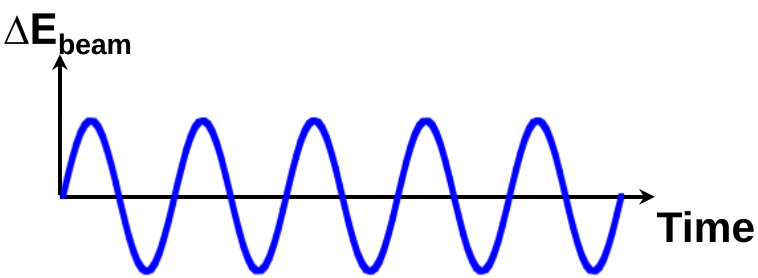
$$\lambda_w = 2\gamma^2\lambda_L/(1+\frac{K^2}{2})$$

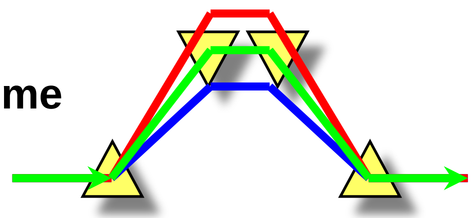
Laser wavelength

- **Electron beam couples to E-field of laser when co-propagating in an undulator**
- **Over one undulator period, the electron is delayed with respect to the light by one optical wavelength**

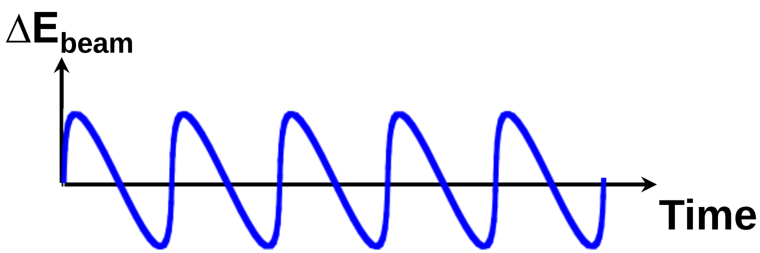
Bunching of the electron beam

ENERGY MODULATION FOLLOWED BY DISPERSIVE SECTION

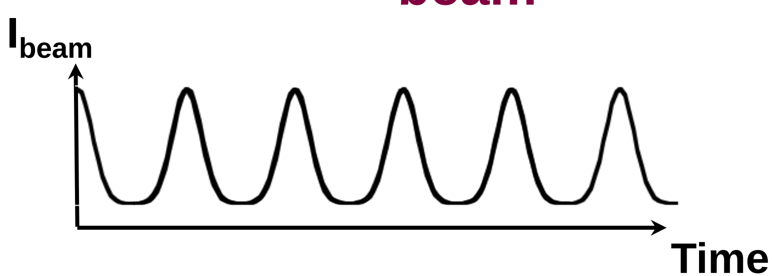




Energy-dependent path length



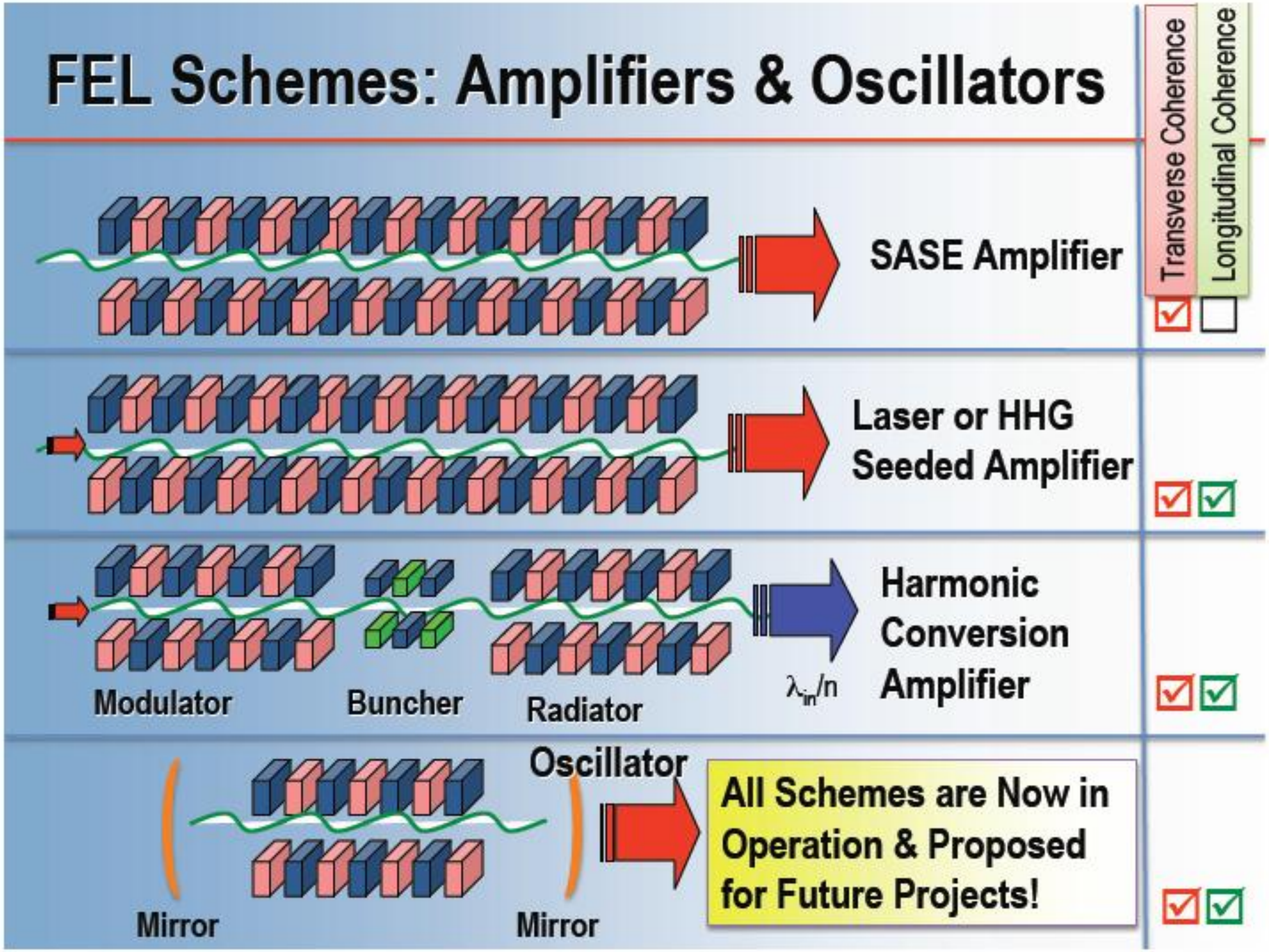
Induced current modulation in the electron beam



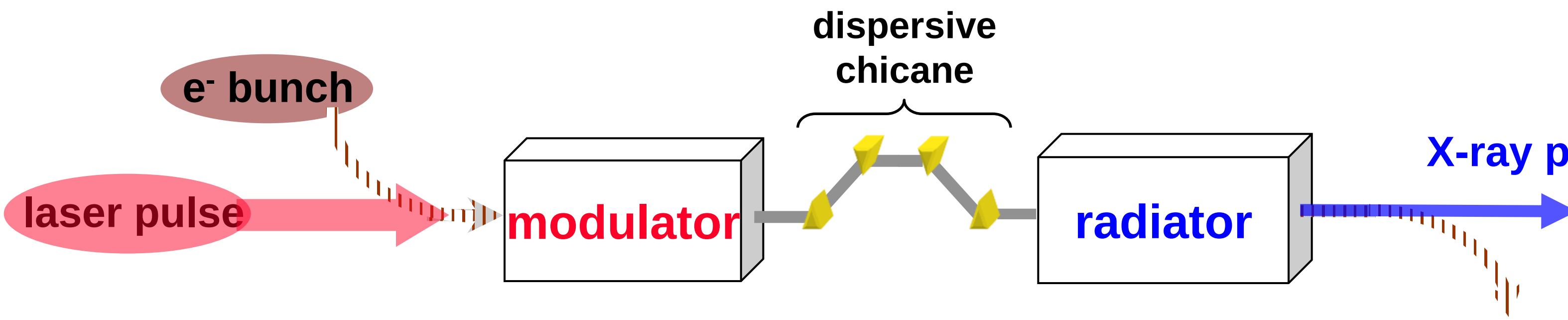
For modest dispersion, the effect is to induce deep modulation in the electron charge density

For very strong dispersion, the effect is to produce very fine structure in the longitudinal phase space – "echo effect" shown on the next slide

FEL Schemes: Amplifiers & Oscillators



High-gain harmonic generation (HGHG)



$$\lambda_{laser} = \lambda_{x-ray}^{modulator} = \frac{\lambda_{undulator}^{modulator}}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

$$\lambda_{x-ray}^{radiator} = \frac{\lambda_{x-ray}^{modulator}}{n} = \frac{\lambda_{undulator}^{radiator}}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

L.-H. Yu et al, Science 289 932-934 (2000)

High-gain harmonic generation (HGHG)

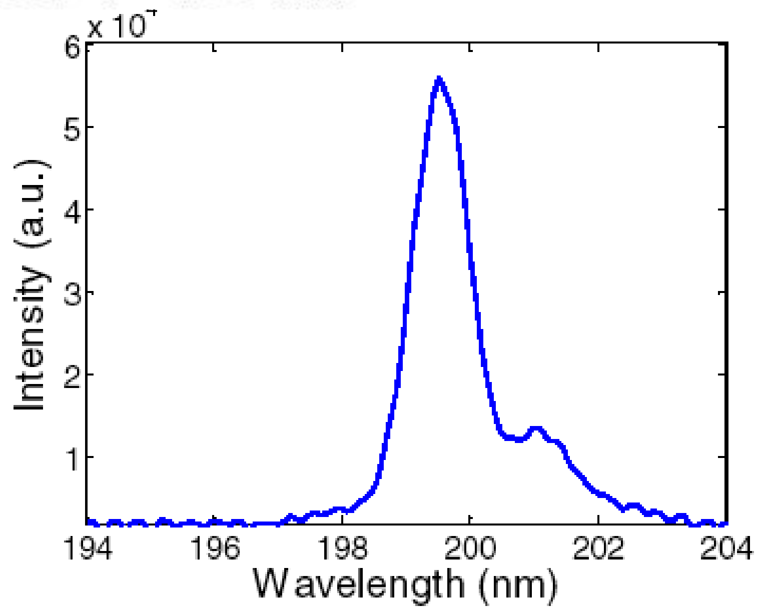
795-199 nm DEMONSTRATED AT BROOKHAVEN SDL

199 nm

795 nm

Resonant at 795/4 =199 nm

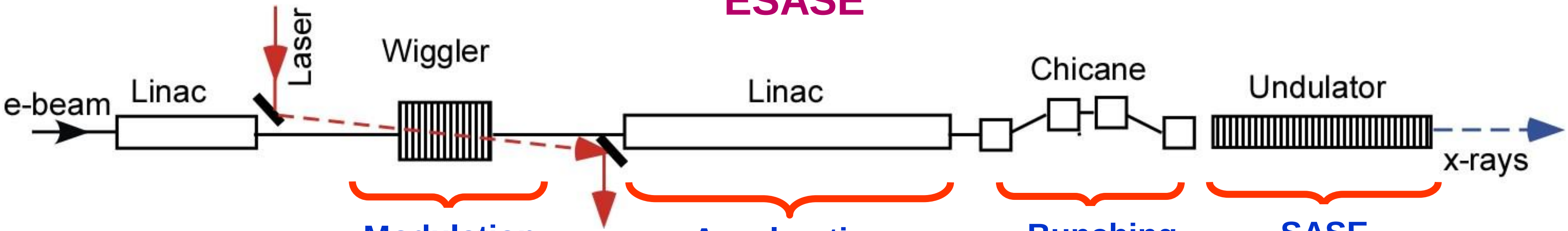
Resonant at 795 nm

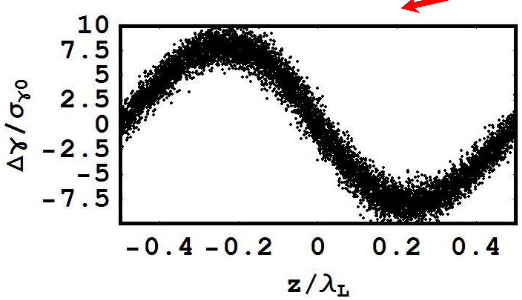


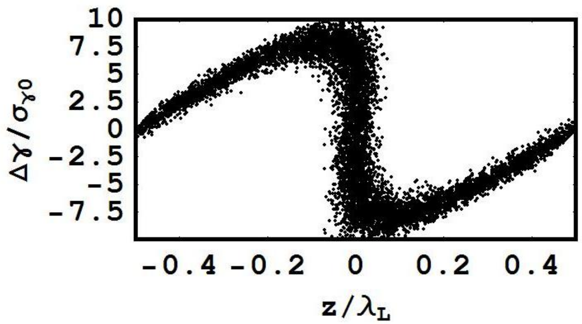
L.-H. Yu et al, Phys. Rev. Let. Vol 91, No. 7, (2003)
X.-J. Wang, ICFA Beam Dynamics Newsletter N0. 42, (2007) http://www-bd.fnal.gov/icfabd/Newsletter42.pdf

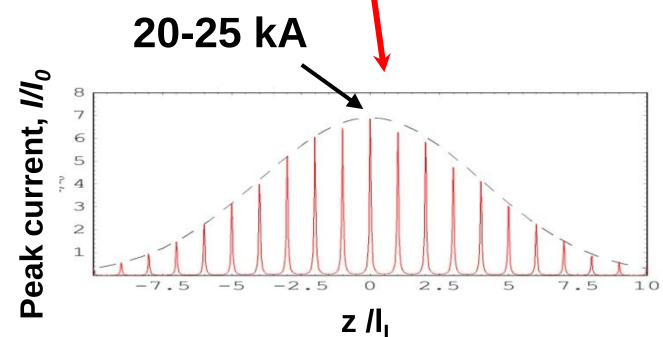
Optical manipulations techniques

ESASE

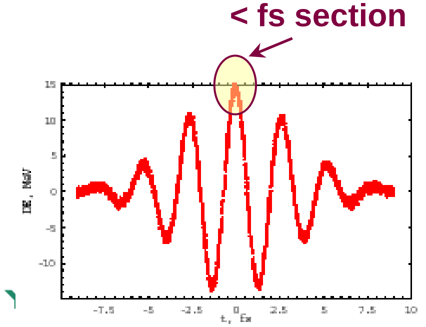








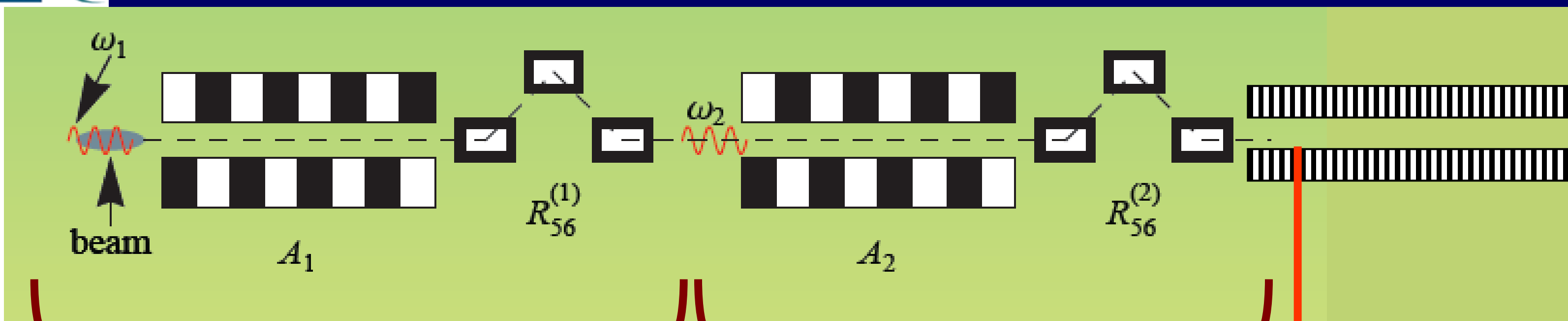
- Precise synchronization of the x-ray output with the modulating laser
- Variable output pulse train duration by adjusting the modulating laser pulse
- Increased peak current
- Shorter x-ray undulator length to achieve saturation

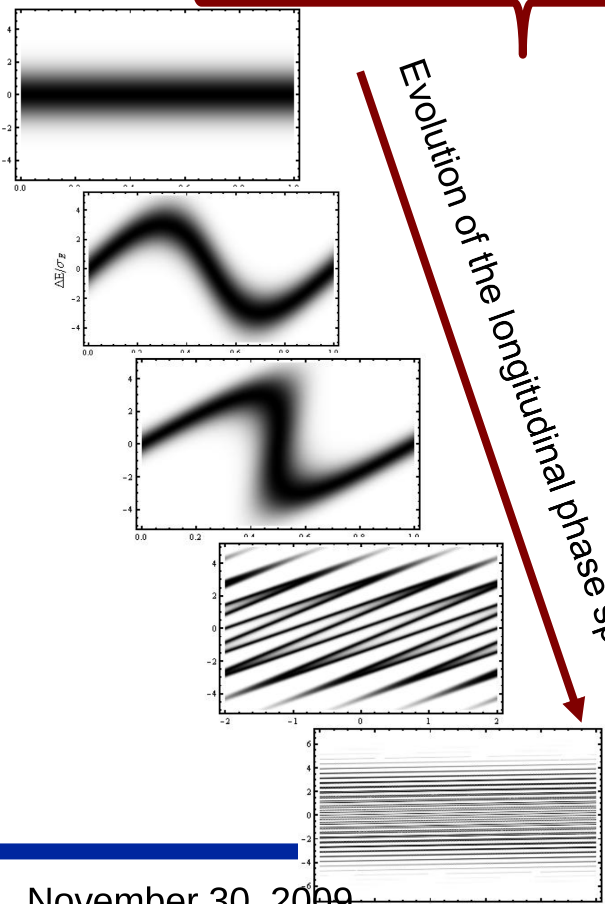


A. Zholents, Phys. Rev. ST Accel. Beams 8, 040701 (2005)

Echo effect for harmonic generation

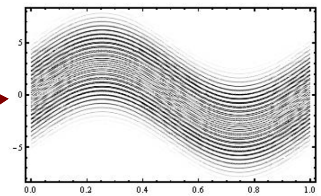
Collaborating with SLAC in "ECHO-7" demonstration experiment





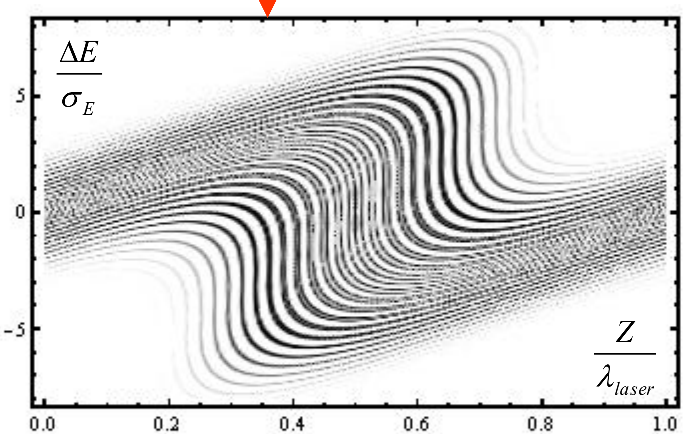
Evolution of the longitudinal phase space

G. Stupakov, SLAC-PUB-13445 (2008)



Bunching decreases only with 3rd power of harmonic

$$b_n \sim 0.4\, n^{-1/3} \frac{\Delta E}{\sigma_E}$$

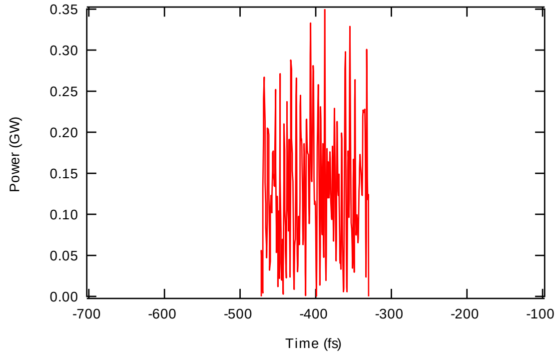


Strong micro-bunching

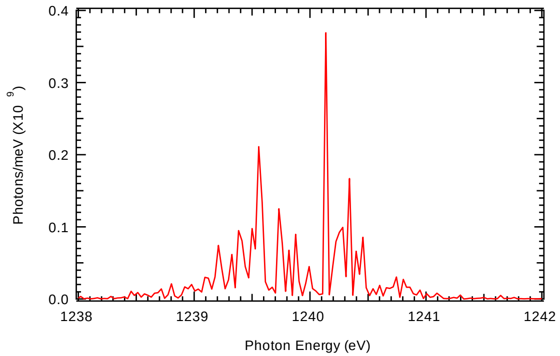
Seeded FEL

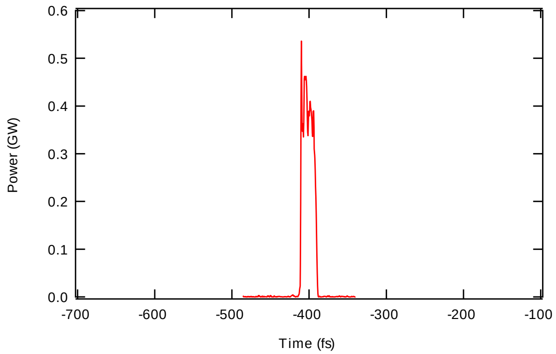
ENHANCED CAPABILITIES FOR CONTROL OF X-RAY PULSE

Pulse profile | **Spectrum**

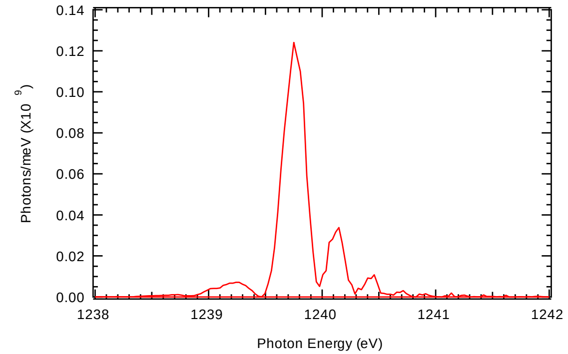


SASE



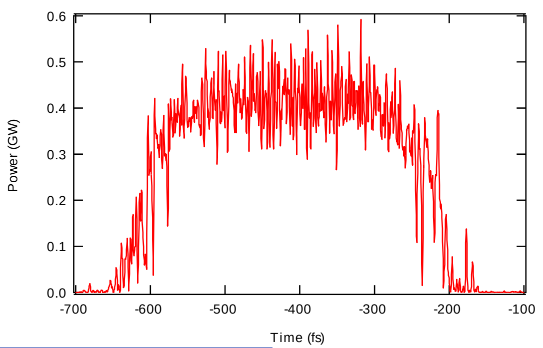


25 fs seed

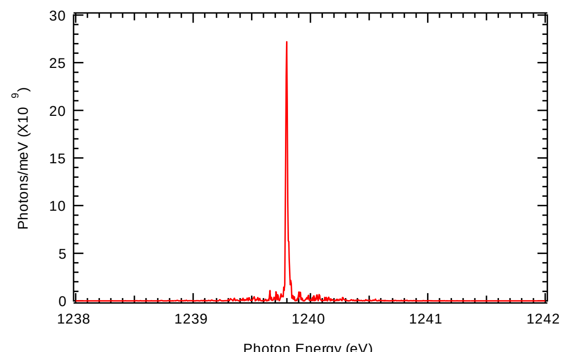


Seeded FEL close to

transform limit



500 fs seed

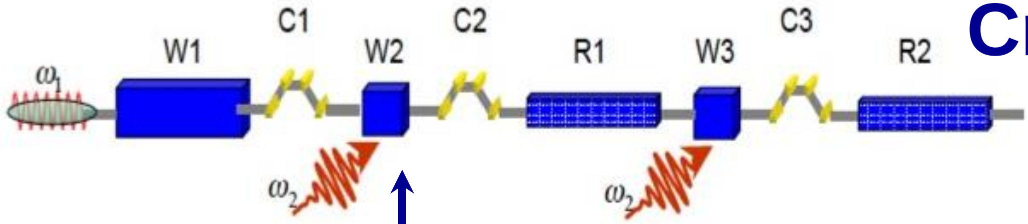


Electron beam is 1.5 GeV, energy spread 100 keV, 250 A current, 0.25 micron emittance; laser seed is 100 kW at 32 nm; undulator period 1 cm

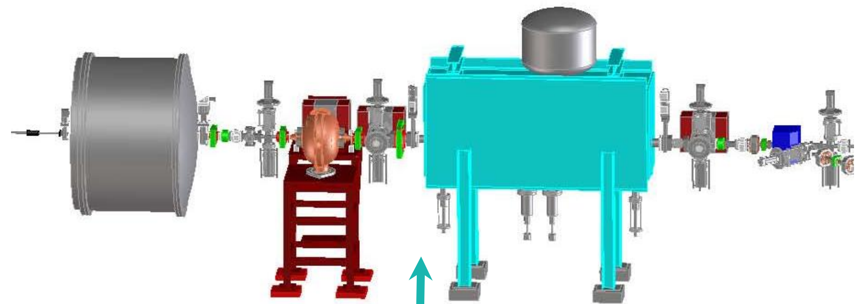
Challenges

- Challenges generally are a superset of ERL and Ulimate Rings
- High brightness guns
- Low emittance beam transport
- Stability
- Details of seeding processes.

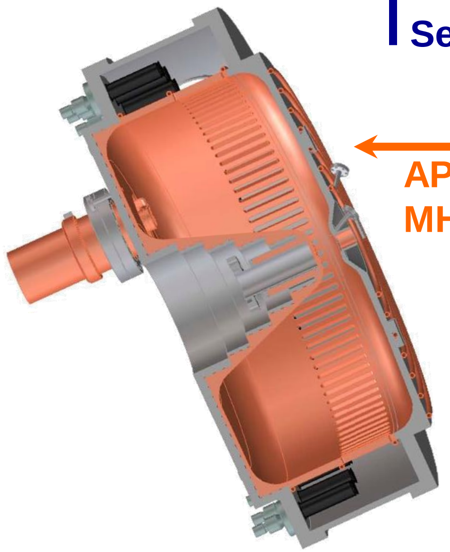
Critical accelerator design and R&D at LBNL



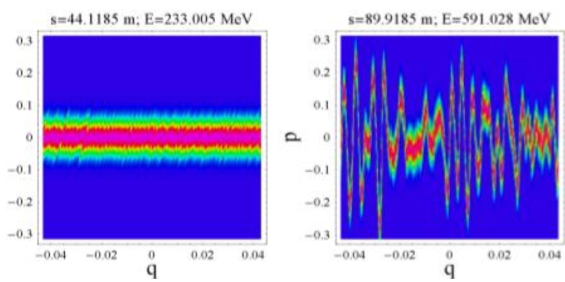
Seeded FEL design



APEX injector design

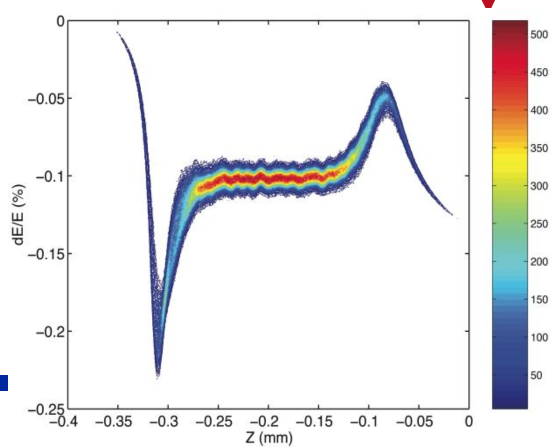


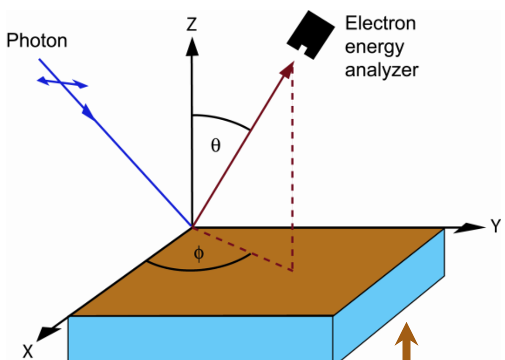
APEX CW VHF photo-gun cavity
MHz bunch rate



Control over the microbunching instability

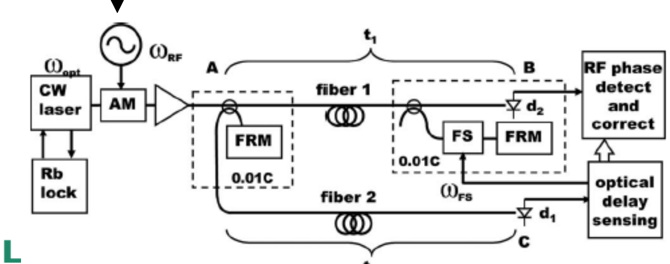
High-resolution modeling with LBNL code IMPACT



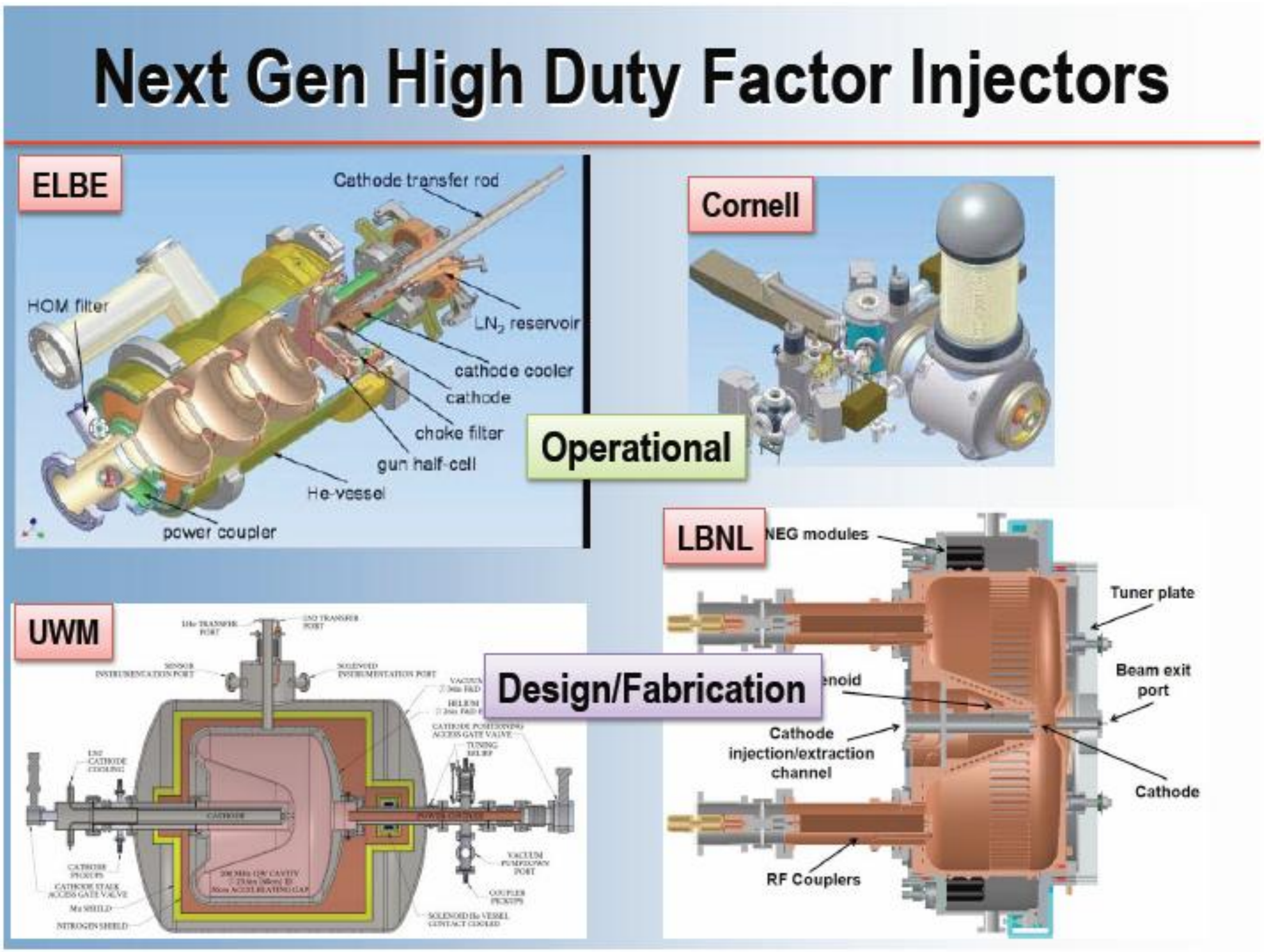


High-efficiency, low emittance photocathodes

Ultra-precision timing & synchronization systems

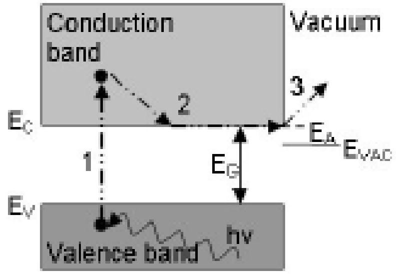


ChallengesElectron Sources (compare Fernando's Lecture)



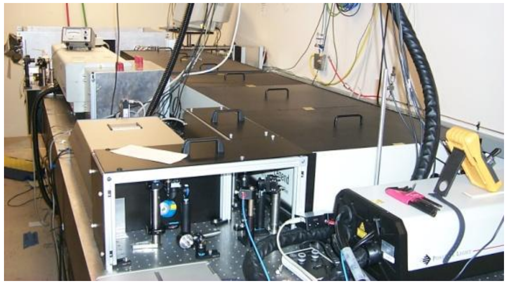
Injector Defines the Beam Quality

EMITTANCE, CHARGE, ENERGY SPREAD, BUNCH RATE

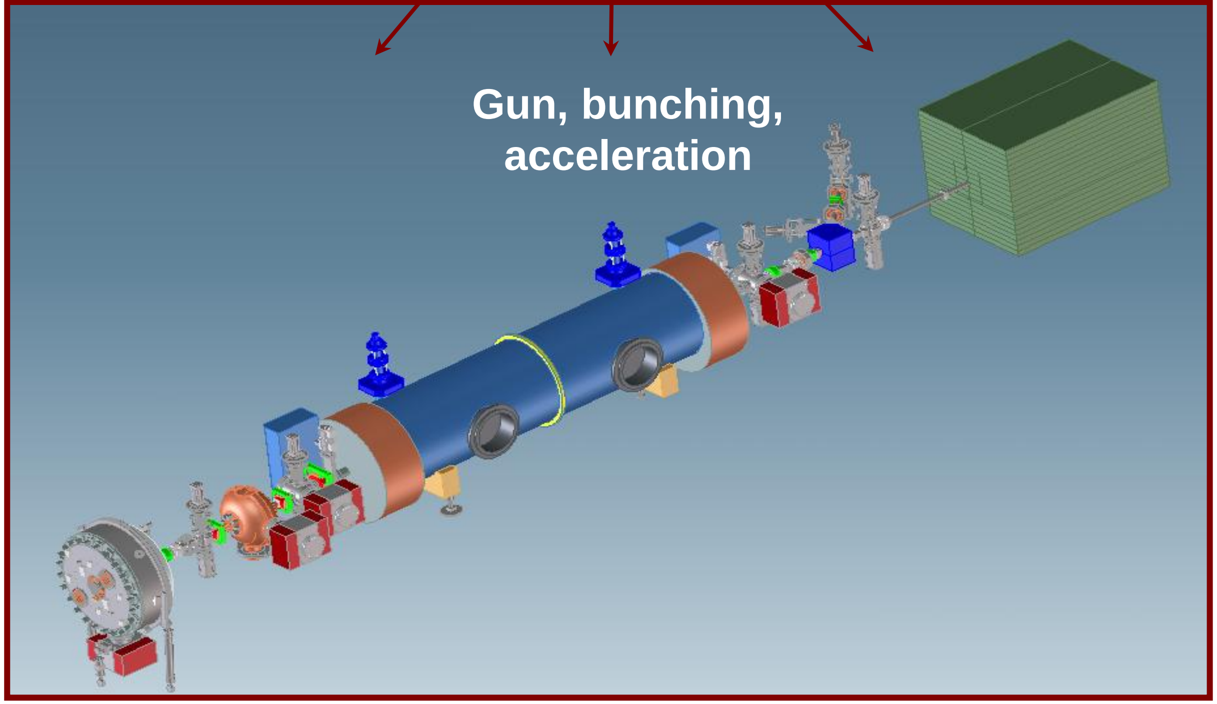


Low emittance, high quantum efficiency cathodes

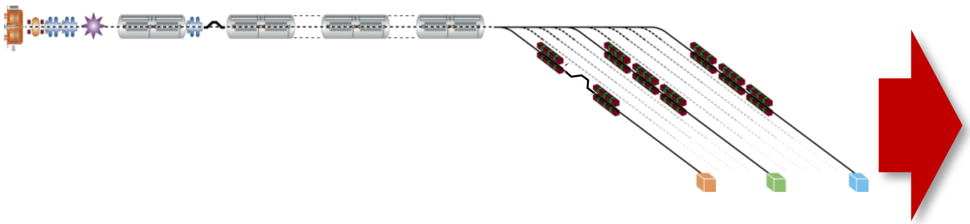
Integrated systems

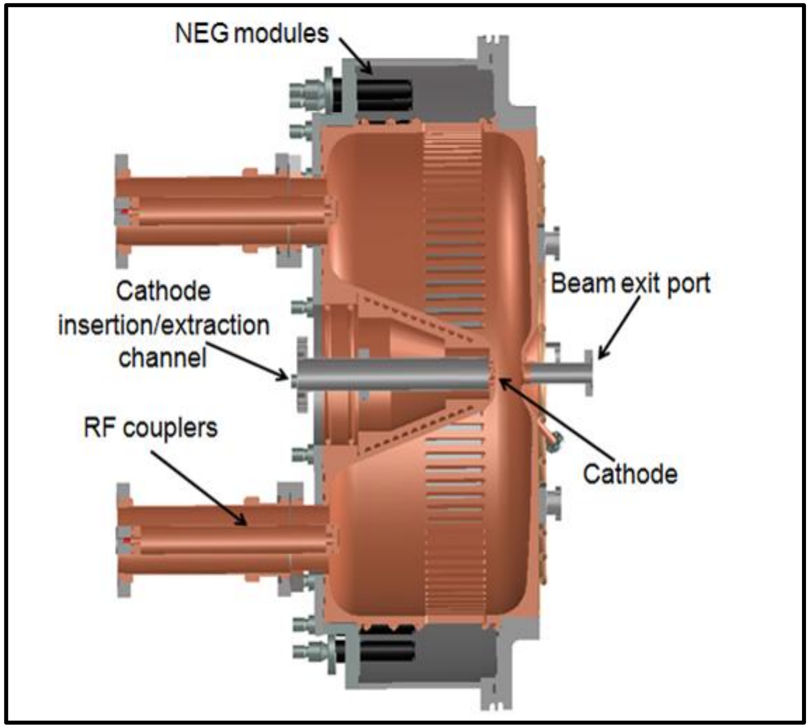


Photocathode laser systems including pulse shaping



A high rep-rate electron gun (LBNL)



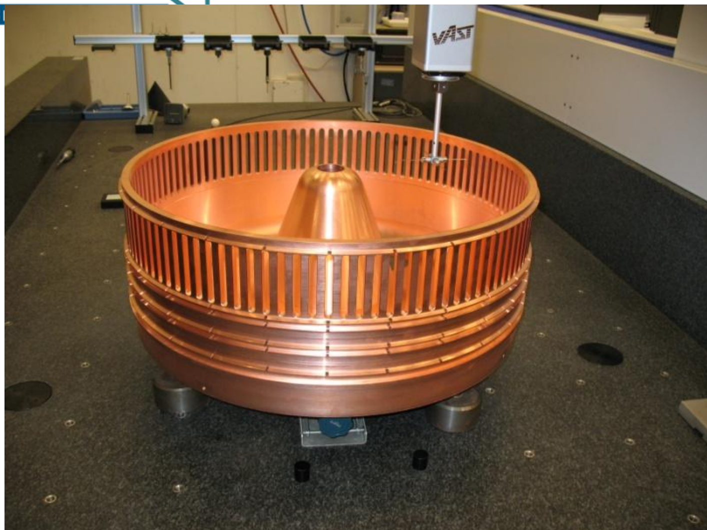


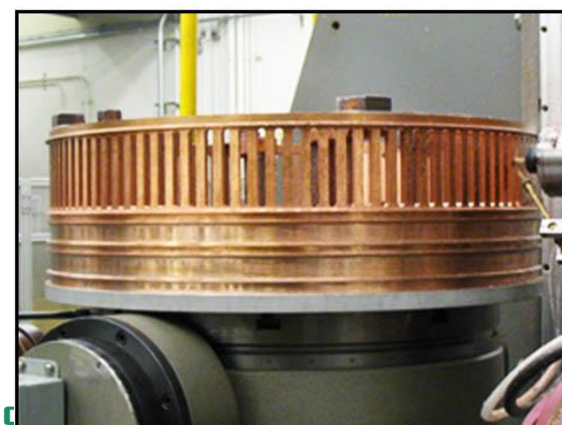
Simultaneous injector requirements:

- Repetition rates of up to ~ 1 MHz
- $<10^{-6}$ m normalized beam emittance
- Compatibility with magnetic fields at the photocathode
- Variable bunch length for controlling space charge effects
- Final beam energy > 500 keV with gradients > 10 MV/m
- Charge per bunch up to ~1 nC
- Accommodates a variety of cathode materials
- 10^{-11} Torr vacuum capability

K. Baptiste, et al., NIM A 599, 9 (2009)

Cavity Fabrication





- ***Cavity has successfully passed conceptual and final design review by external committee and is now in fabrication***
- ***120 kW power supply is in procurement***

High Brightness Photocathodes

Reduce emittance

FEL amplification needs very small emittance, ε

$$\varepsilon < \frac{\text{FEL wavelength}}{4\pi}$$

Acceleration to high energy reduces geometric emittance

$$\varepsilon \propto \frac{1}{\text{electron energy}}$$

Increase efficiency

Metal: **QE = 5×10^{-5}, 1 MHz, 4.65 eV, 5% IR-UV**

- kW of IR needed, psec pulses

- robust, fast emission

Semiconductor: **QE = 5×10^{-2}, IR**

- ~W of IR needed

- fragile, slow emission, current limited

Smaller initial emittance means

smaller accelerators for fixed wavelength

- *lower cost*

shorter wavelength for fixed accelerator

- *wider capabilities*

Higher efficiency means

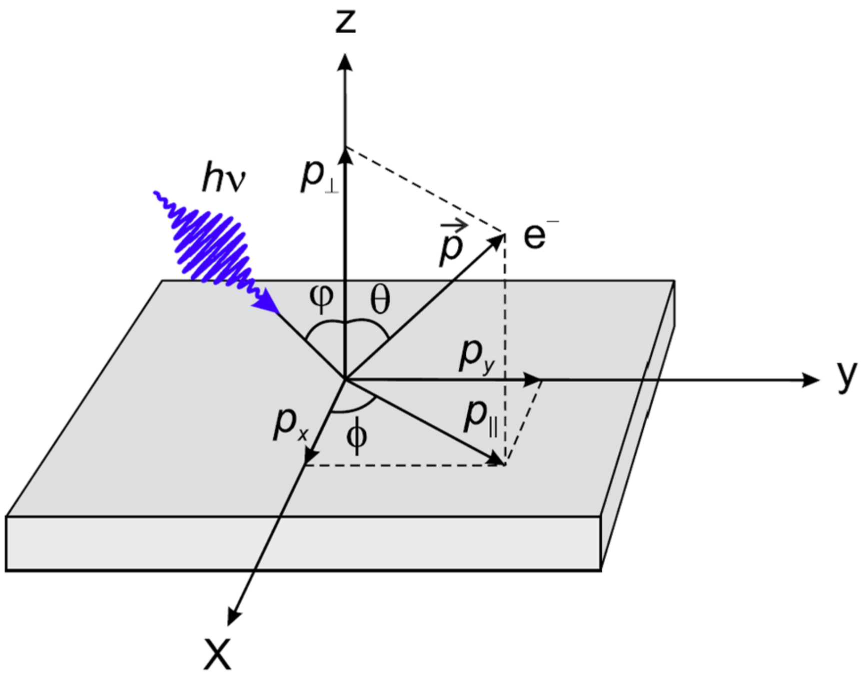
smaller lasers for fixed repetition rate

- *lower cost*

higher repetition rate for fixed laser power

- *increased capabilities*

Characterizing Photocathodes

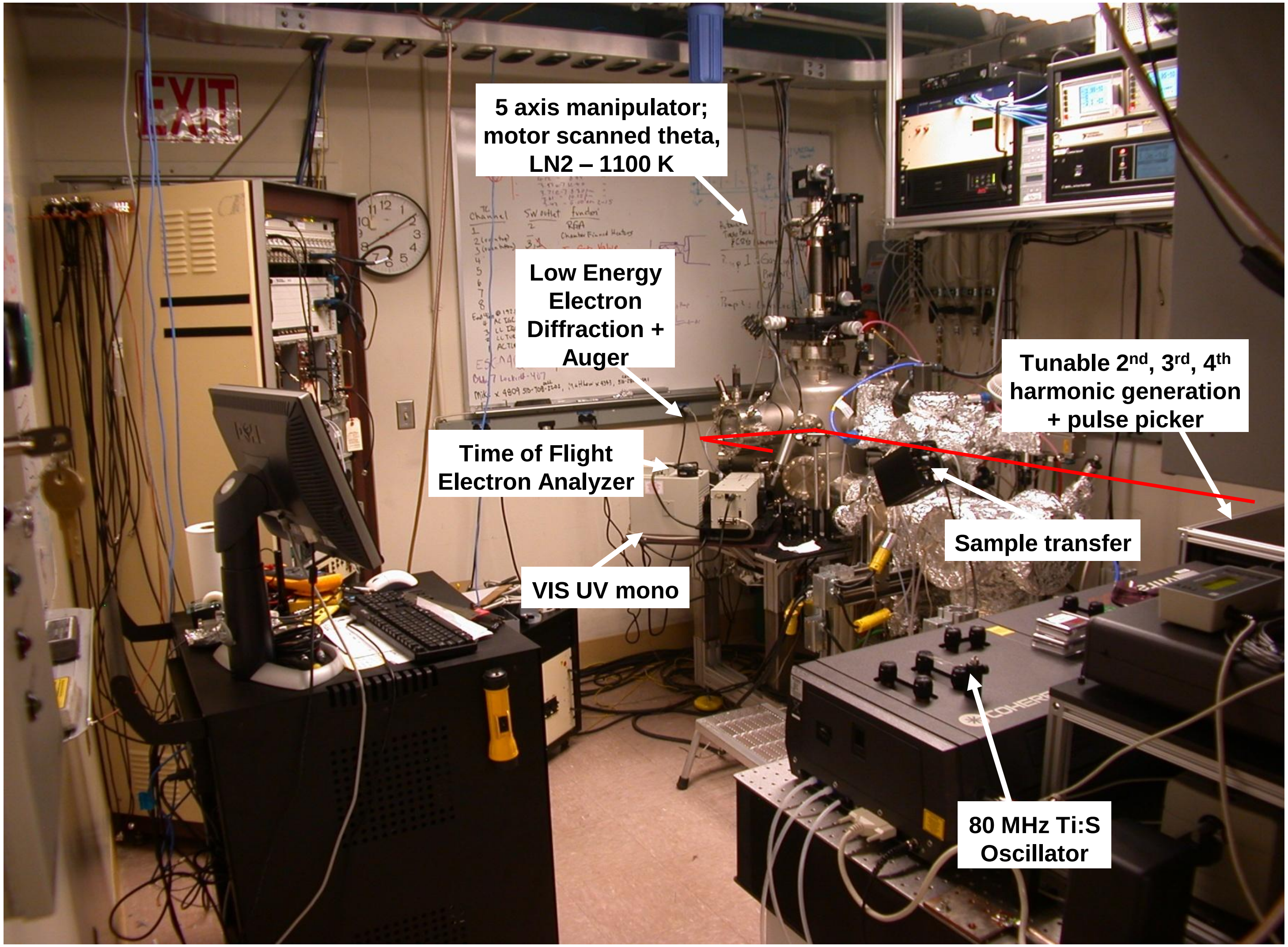


- Full measurement of momentum distribution and yield as function of
  - Polarization
  - Photon energy (2–6 eV)
  - Photon incidence angle
  - Surface preparation

- Techniques
  - Ultra-low energy angle resolved electron spectroscopy
    - Kinetic energies 0–1eV
  - Angle resolved electron yield

- Materials
  - Metals
  - NEA Semiconductor: GaAs:Cs:O
  - PEA Semiconductor: $CsTe_2$, Alkali Antimonides eg. $SbNa_2KCs$

Photocathodes Lab (one of two)

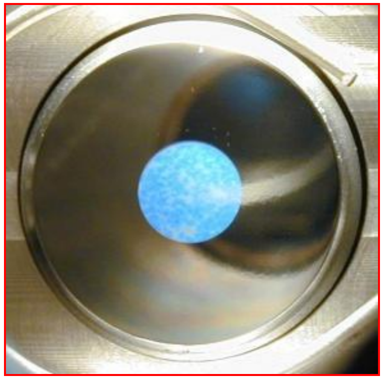


Photocathode Materials

Alkali Antimonides eg. $SbNa_2KCs$

- Fast
- Reactive; requires UHV ~ 1e-10 mBar pressure
- High QE (typ. 10%)
- No pulse charge saturation
- Requires green light (efficient conversion from IR)
- nC, 1 MHz….40 mW of IR required (laser oscillator)
- Unproven at high rep rate and high average current

Cs_2Te (used at FLASH for example)



- Fast
- Relatively robust and un-reactive
  - Can be used in a high gradient rf gun
- High QE; typ. 10%
- No pulse charge saturation
- Requires UV (eg. 3rd harm. of Ti:Sapphire: 5% conversion effic.)
- For 1 nC - 1 MHz reprate, ~ 1 W 1060nm required
- Unproven at high rep rate and high average current

Challenges: Wakefields and Beam Dynamics

Wakefields & Beam Dynamics

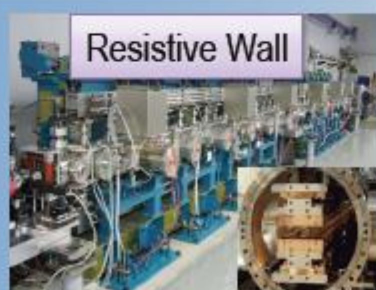
Longitudinal Space Charge

$$Z_{LSC}(k) \approx \frac{iZ_0 c}{4\pi\gamma^2}\left(1 + 2\ln\frac{r_w}{r_b}\right)k$$

Coherent Synchrotron Radiation

$$Z_{CSR}(k) \approx \frac{2Z_0\Gamma\left(2/3\right)}{3^{1/3}\rho^{2/3}}\left(\frac{\sqrt{3}}{2} + i\frac{1}{2}\right)k^{1/3}$$

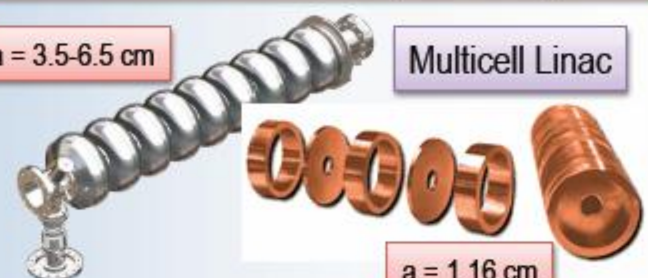
Resistive Wall



$$Z_{RW}(k) \approx \frac{2s_0}{cb^2}\left(\frac{i\,\mathrm{sgn}(ks_0)+1}{(ks_0)^{1/2}} - \frac{i(ks_0)}{2}\right)^{-1}$$

Multicell Linac

a = 3.5-6.5 cm

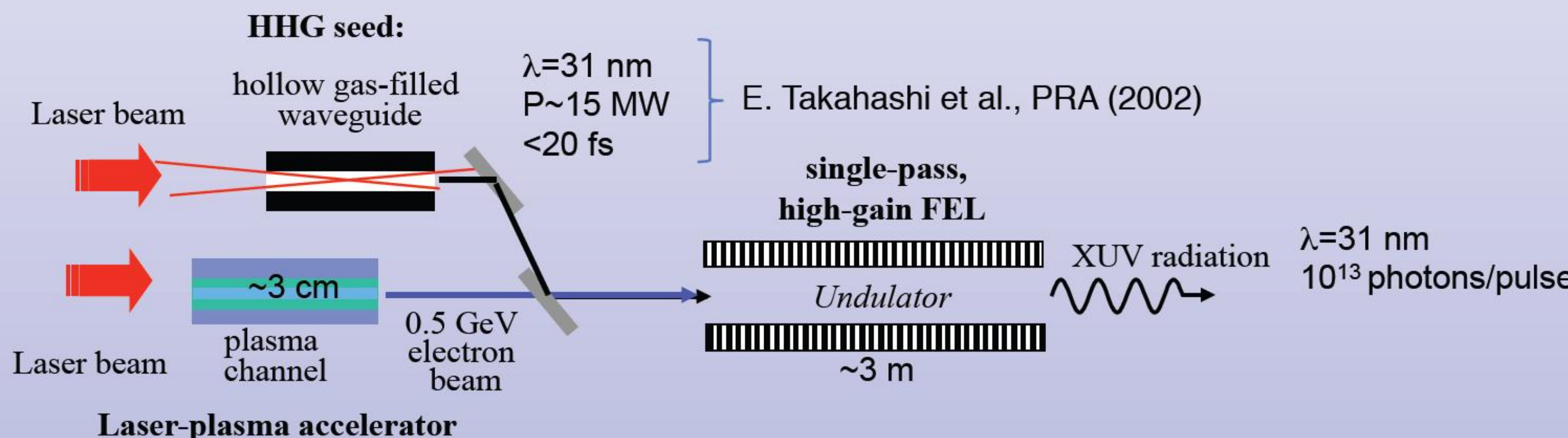


a = 1.16 cm

$$Z_{Linac}(k) \approx i\frac{Z_0}{\pi a^2 k}\left[1 + \frac{\alpha(1+i)L}{a}\left(\frac{\pi}{kg}\right)^{1/2}\right]^{-1}$$

FEL using Laser Wakefield Accelerator

- Approach:
  - Produce compact multi-GeV e-beam using LPA
  - Send e-beam through undulator
  - Seed using high harmonics

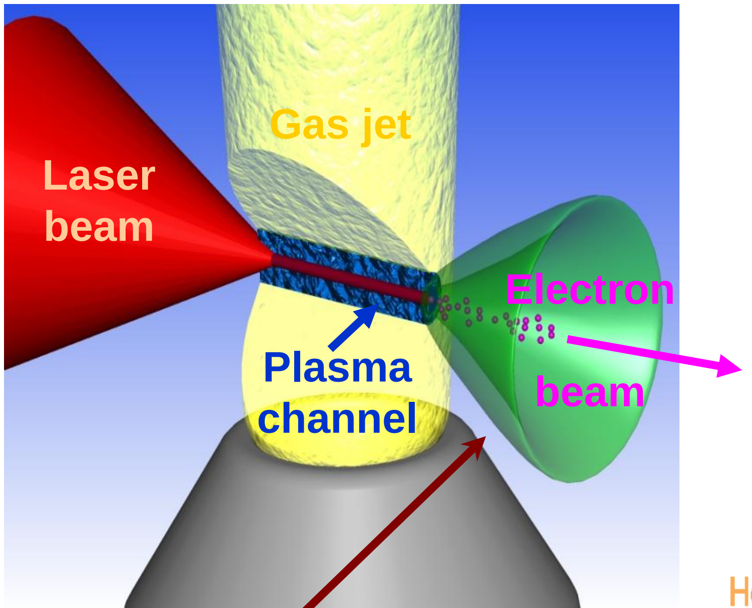


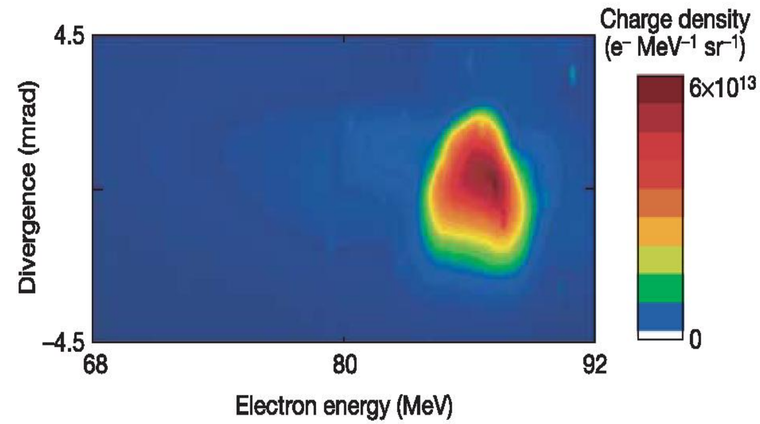
Schroeder et al., Proc. of FEL06 (2006)
Jaroszynski et al., Philos. Trans. R. Soc. A (2006)
Grüner, et al., Appl. Phys. B (2007)

Laser wakefield accelerator

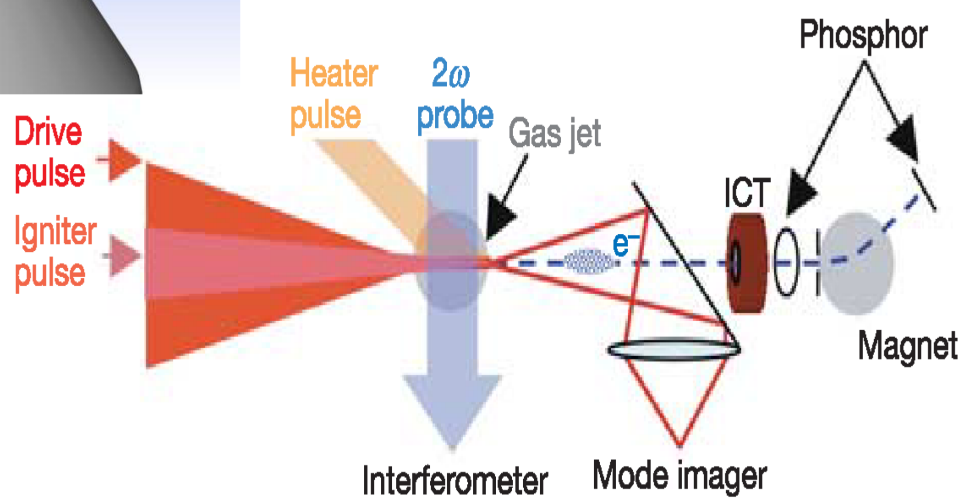
✓ **Step 1: Electron gun: 100 MeV in < 2mm**

- ~ 1% energy spread
- ~ 1 mm-mrad emittance





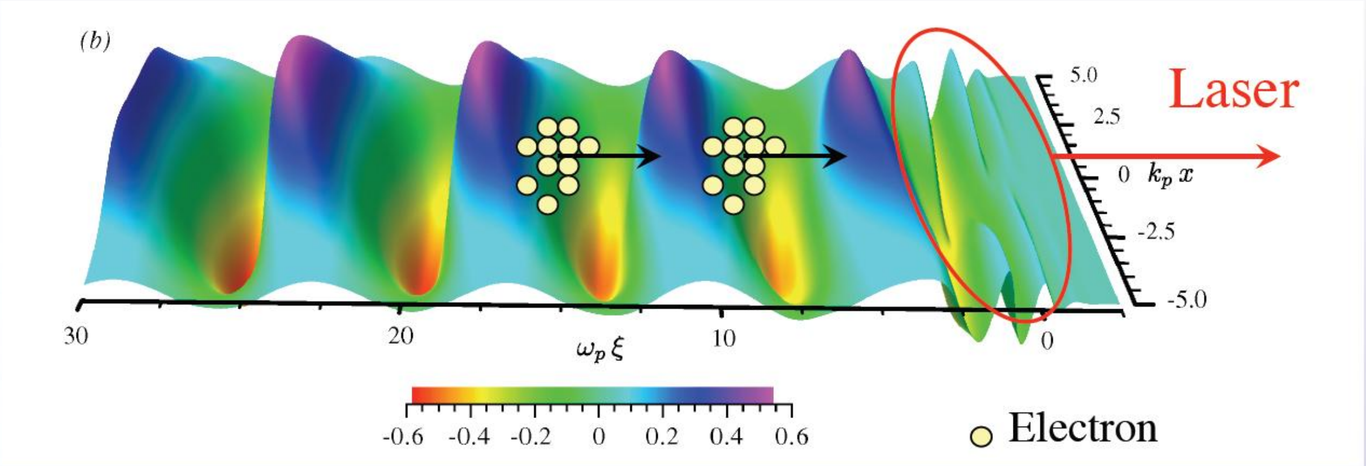
+ CSR from emerging beam



C. G. R. Geddes,et al, Nature,431, p538, 2004

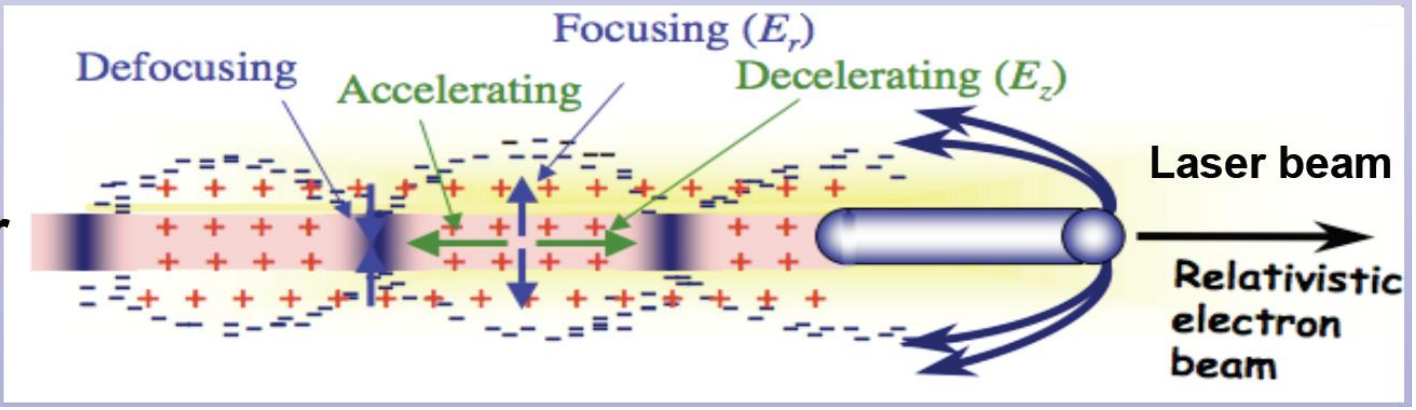
Principle of LWFA

Linear



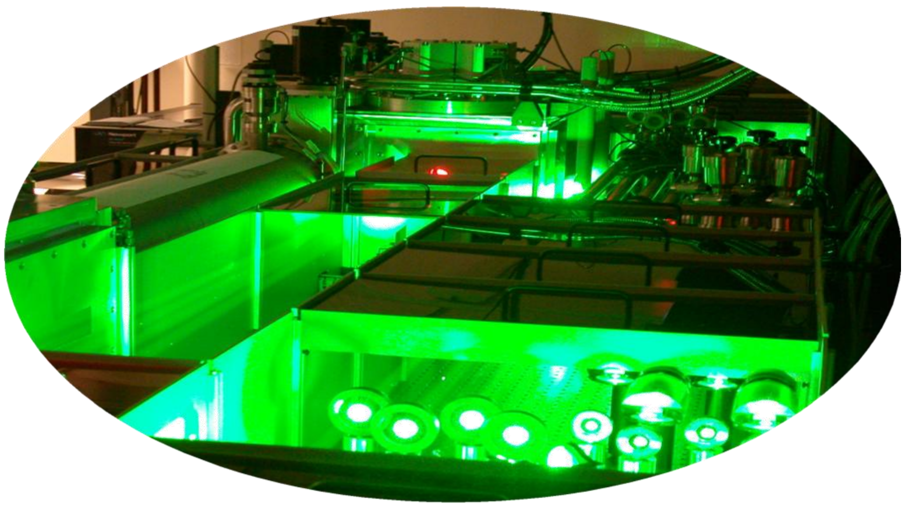
- Laser driver--Tajima&Dawson, PRL'79
- Beam driver--P. Chen et al., PRL'85
- E-fields: 10 – 100 GV/m
- Phase velocity wake=Group velocity driver

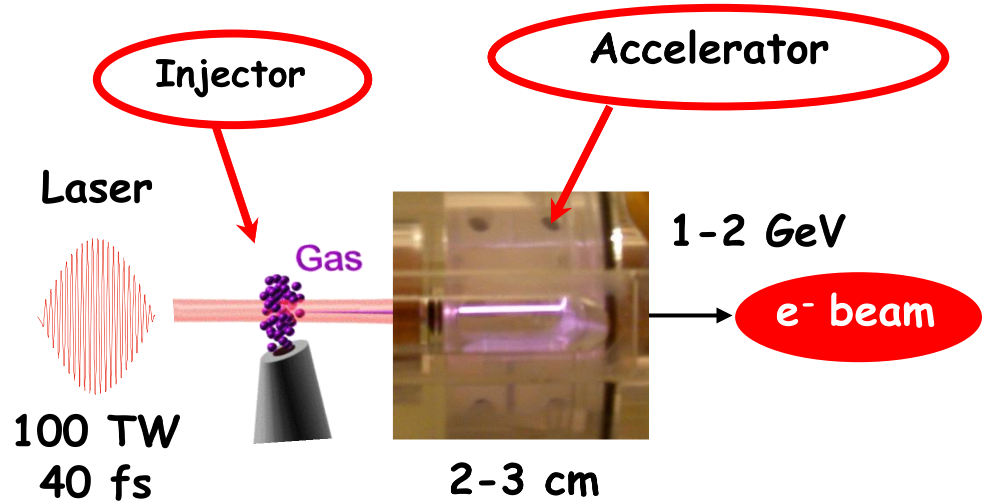
Non-Linear

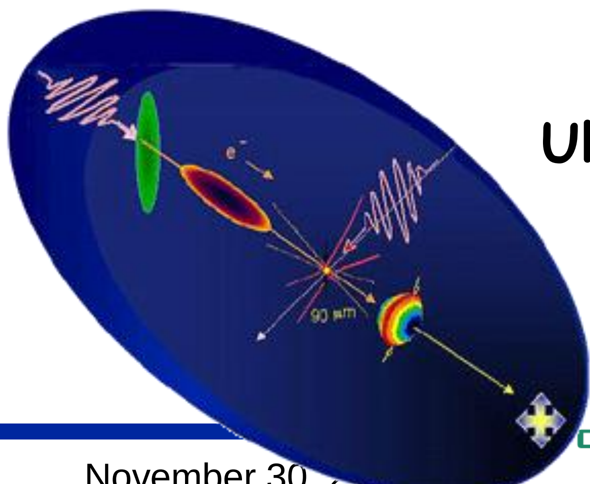


Laser wakefield accelerator

- **Step 2: Accelerator: 1 GeV in < 5 cm**







Ultrafast x and γ -rays from Thomson scattering

Also use the electron beam in an FEL

A LWFA based SASE FEL

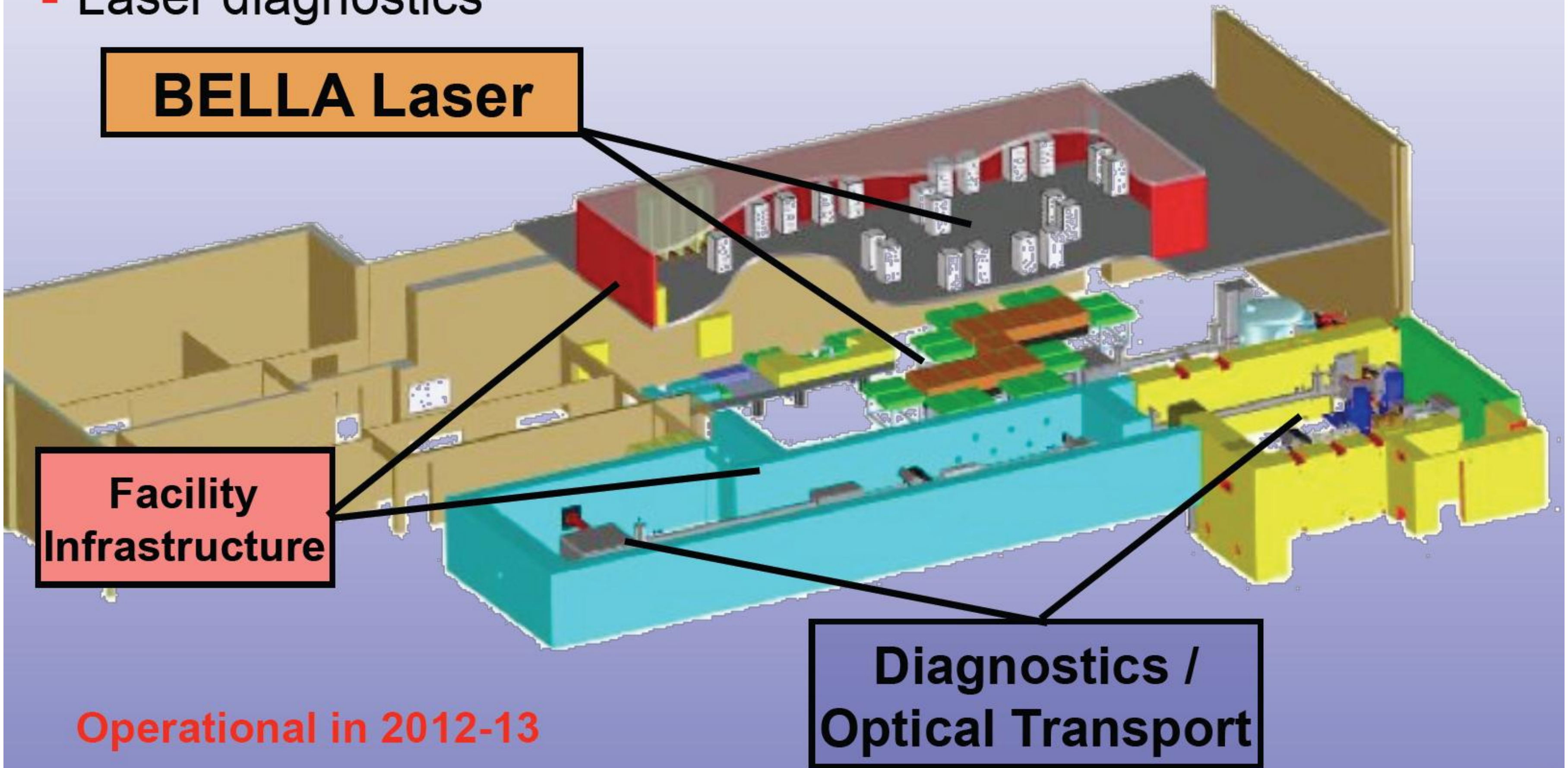
LWFA beam parameters	
Normalized energy, γ	2000
Normalized emittance	1 mm mrad
FWHM duration	20 fs
Charge	0.5 nC
Peak current	25 kA
Energy spread (projected)	0.01

- Ongoing research in l'OASIS laboratory
- Will peak current be preserved ?
- Will emittance be preserved ?
- Will ΔE/E be low enough ?
- Rep rate, efficiency

FEL parameters	1 GeV LWFA	0.25 GeV LWFA
Normalized beam energy	2000	500
Undulator wavelength	1 cm	1 cm
Undulator strength	1	1
Radiation wavelength	2 nm	30 nm
FEL parameter	$2 \cdot 10^{-3}$	$5 \cdot 10^{-3}$
Saturation length	4.7 m	1.8 m
Photons/pulse at saturation	10^{13}	10^{14}
Beak brightness (ph./s/mm^2/mrad^2/0.1%BW)	$5 \cdot 10^{30}$	10^{29}

BELLA Facility at LBNL

- High rep rate (1 Hz), Petawatt class laser (>40 J in < 40 fs)
- Laser bay and target area
- Laser diagnostics



Operational in 2012-13

Summary

- FELs
  - Extremely high peak brightness, potential for very high average brightness, potentially full (longitudinal + transverse) coherence up to short wavelengths, ultimate performance requires substantial development program (risk)
- Laser Plasma Wakefield Accelerators
  — Ultra Compact, Naturally very short pulses, need further laser development (to raise average beam power)

- Many interesting topics (for theses) in all areas, Berkeley (LBNL) and Stanford (SLAC) are heavily involved in multiple areas.

Thanks to J. Corlett, J. Murphy, W. Leemans for several illustrations